UNSTEADY-STATE DIFFUSION OF MOISTURE IN GIANT TIMBER BAMBOO (*PHYLLOSTACHYS BAMBUSOIDES* SIEB. & ZUCC.)

Perry N. Peralta

Assistant Professor
Department of Forest Resources
Clemson University
Clemson, SC 29634-1003

and

Andy W. C. Lee

Professor
Department of Forest Resources
Clemson University
Clemson, SC 29634-1003

(Received July 1994)

ABSTRACT

This paper presents the results of a study to determine the rate of moisture movement in giant timber bamboo (*Phyllostachys bambusoides* Sieb. & Zucc.) when exposed to three different temperatures (20 C, 30 C, and 40 C) at two ranges of moisture content (0 to 7.5%, and 7.5 to 15%). Edge-coated samples measuring 6 mm (R) × 30 mm (T) × 150 mm (L) were exposed to a given temperature-humidity combination in a conditioning chamber. The weight of a sample was continuously monitored over time and the weight-time data were analyzed using the Boltzmann solution to the unsteady-state form of Fick's diffusion equation.

Diffusion coefficients ranged from 7.3×10^{-12} to 7.8×10^{-11} m²/sec. They were greater at the higher moisture content range. They increased with temperature such that the Arrhenius equation fits the data well, giving mean activation energies of 39,875 and 35,889 J/mole for the lower and higher moisture ranges, respectively. The calculated diffusion coefficient was approximately twice as high during desorption as during adsorption.

Keywords: Diffusion, Fick's law, activation energy, bamboo.

INTRODUCTION

Pressures on existing timber resources brought about by an ever-increasing world population have led to renewed efforts to find alternative raw materials for many of the traditional uses of wood. One such promising substitute material is the bamboo, an arborescent grass. Bamboos grow more rapidly than any other plant on earth, sometimes growing as fast as 1.2 m in a single day (Farrelly 1984). Most species reach their maximum height of 15 to 30 m in 2 to 4 months, and full maturity in about 3 to 8 years. Certain species are able to tolerate warm tropical climates, while others are known to survive in the very cold regions of the Andes and Himalayas.

Although bamboos thrive naturally in all continents except Europe (Liese 1987), most are found in Asia. The United States has but two native species (both belonging to the genus *Arundinaria*), growing mainly in the southern states south of Virginia and westward to southern Missouri (Glenn 1950). Oriental bamboos were first introduced into the United States around the mid-1800s (Adamson et al. 1978) of which the giant timber bamboo (*Phyllostachys bambusoides*), a native species of southern China, is the most widely planted (Mc-

Wood and Fiber Science, 27(4), 1995, pp. 421–427

Clure 1957). It was first brought to the United States at Burroughs, Georgia, and then planted in 1889 at what is now the Agricultural Research Services' Plant Introduction Station in Savannah, Georgia, which subsequently distributed the species to several hundred locations in the United States (Chen 1973). The *Phyllostachys* species are evergreen, but old leaves are replaced in the spring each year. The maximum diameter (about 0.14 m) of the shoot is attained at, or soon after, emergence from the soil; and within 6 to 8 weeks, new culms reach full height of about 18 m. In a bamboo yield study at the Plant Introduction Station, a yield of 0.71 ton per acre per year was obtained for the giant timber bamboo during an 8-year establishment period; once the grove had been established, the long-term average yield increased to more than 4.0 tons per acre per year (Adamson et al. 1978). This figure is lower than the 10.3 tons per acre per year reported by McIlhenny (1945) for a plantation in Louisiana, but is comparable to the oven-dry weight yields of 1.83 to 3.16 tons per acre per year reported by Sturkie et al. (1968) for a plantation in Alabama. In the latter study, the annual yield of bamboo is found to be twice as much as that of loblolly pine.

Past research on the utilization of bamboos in this country has focused mainly on the pulp and papermaking properties (Naffziger et al. 1960). Limited studies are on the use of bamboo as reinforcement in place of steel in portland cement concrete (Glenn 1950); its suitability as structural board (Naffziger et al. 1960); and its seasoning, and preservative and water-repellent treatments (Glenn 1956). To maximize bamboo utilization, Clemson University is undertaking investigations of the basic properties and the processing characteristics of giant timber bamboo. The work on its mechanical properties has already been reported in an earlier publication (Lee et al. 1994). This paper presents the results of a study to evaluate the diffusion coefficient of moisture in bamboo. The information will be valuable in determining the rate of moisture movement in the material and therefore is of practical importance in the processing and utilization of giant timber bamboo, particularly in relation to the bamboo's drying characteristics and interaction with water when in service.

MATERIALS AND METHODS

Giant timber bamboo (*Phyllostachys bambusoides* Sieb. & Zucc.) specimens measuring 6 mm (R) × 30 mm (T) × 150 mm (L) were obtained from strips that were not used for the mechanical tests (Lee et al. 1994). The preplaned wide faces of the samples were slightly sanded to remove any residual skin on the inner surface and epidermal coating on the outer surface. After the oven-dry weight and thickness of each sample were measured, the edges were coated with two thin layers of epoxy to restrict diffusion only to the thickness (or radial) direction. Twenty-four samples were prepared, with four replicates allocated randomly among the two moisture content range × three temperature treatment combinations. At a given temperature two adsorption runs were made, one starting from zero to approximately 7.5% MC and the other from 7.5 to about 15% MC. The study was performed as a two-factor factorial experiment in a completely randomized design, with temperature (20 C, 30 C, and 40 C) and moisture content range (0 to 7.5% and 7.5 to 15%) as factors. Desorption experiments were also conducted at 30 C by subjecting the adsorption samples (after they had equilibrated to a moisture content of 15%) to a relative humidity of 40% (EMC = 7.5%). The adsorption and desorption data at 30 C were analyzed using paired t-test.

Before the start of the experimental runs at each desired temperature, five samples were first dried in an oven set at 103 ± 2 C for at least 24 h. Four of the oven-dry samples were then kept inside a conditioning chamber maintained at the first RH level (approximately 40%) for them to come into equilibrium with this atmosphere and be ready for use as the four experimental units at the next higher RH level (approximately 80%). The fifth oven-dry sample was immediately covered with two layers of plastic wrap, enclosed in a polyethylene bag,

and then kept inside a temperature-controlled cabinet for about 30 min to permit the sample to reach the same temperature as that of the conditioning chamber. At the predetermined time, the sample was unwrapped and exposed to the desired temperature and relative humidity maintained inside the conditioning chamber. The sample weight was continuously monitored to within 0.001 g by suspending the sample from a hang-down wire that extended up through a hole in the roof of the chamber to the weighing hook of a Mettler balance, which was situated on top of the conditioning chamber. This arrangement made possible the measurement of the sample's weight variation over time without opening the chamber door nor disturbing the atmosphere inside the chamber. The chamber fan had to be switched off momentarily for about 15 sec during each weight reading to stabilize the circuitry of the balance, which is very sensitive to vibration. After a given run, the sample thickness was measured to the nearest 0.01 mm. This reading and the initial thickness were averaged to obtain the value of 2a in Eq. (2). Towards the end of data collection for the first sample, the next replicate was placed in the oven and prepared the same way as the first one. The process of weight measurements was repeated until all four replicates had been tested. Before the chamber atmosphere was changed to the higher RH level, the four samples that had been pre-equilibrating in the chamber were individually removed and immediately wrapped in plastic, enclosed in polyethylene bags, then transferred to the temperature-controlled cabinet. Once the higher RH level at the given temperature had been established inside the chamber, each sample was then reintroduced to obtain the weight gain as a function of time.

The weight data were used to calculate the average dimensionless moisture content $\bar{E}$ defined as:

$$\bar{E} = \frac{\bar{M} - M_e}{M_i - M_e} \quad (1)$$

where $\bar{M}$ is the average moisture content across the specimen thickness at any given time, M_i the initial moisture content, and M_e the equilibrium moisture content. The integral or average diffusion coefficient $\bar{D}$ was then calculated from the $\bar{E}$ and time data using the following equation (Vergnaud 1991):

$$\bar{D} = \frac{\pi(2a)^2}{16} \frac{(1 - \bar{E})^2}{t} \quad (2)$$

where t is the time from the beginning of the desorption or adsorption step; and 2a, the thickness of the specimen in the direction of diffusion. The above solution (known as the Boltzmann solution) to the unsteady-state form of Fick's law of diffusion requires that: (a) the material act as an infinitely thick solid, (b) the moisture be initially uniformly distributed throughout the specimen, (c) the surface instantaneously attain the equilibrium condition, and (d) the thickness of the material be constant. It has been shown by Stamm (1959) that Eq. (2) can be applied to wood up to the point when the moisture content at the center starts to change, beyond which the sample ceases to act as an infinitely thick solid. This point corresponds to a value of $(1 - \bar{E})$ approximately equal to 0.5.

RESULTS AND DISCUSSION

The criteria for Fickian-type diffusion require that the plot of $(1 - \bar{E})$ versus the square root of time should be linear for at least 50% of the total moisture content change, and that the curve should have no inflection point and should always be concave to the time axis. Typical curves for the diffusion of moisture in bamboo at 30 C are shown in Fig. 1 for samples allowed to adsorb moisture (a) from 0 to 7.5% MC, and (b) from 7.5 to 15% MC. It is clear that the concavity criterion is met; and although there is a slight time lag, R^2 of at least 0.98 were obtained during linear regression analyses of data up to $(1 - \bar{E}) = 0.5$, indicating the applicability of Eq. (2) in calculating the integral diffusion coefficient of moisture in bamboo. Researches on moisture movement in wood have also successfully applied the above equation to calculate the integral dif-

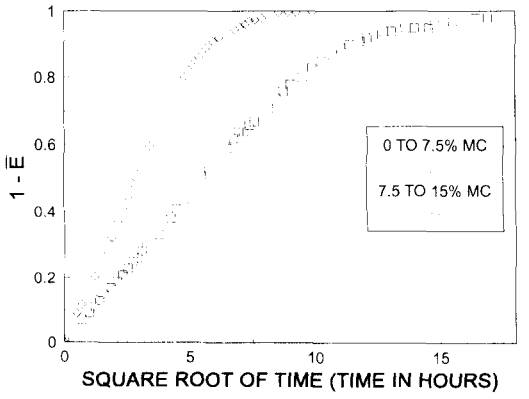

FIG. 1. Scatter plot of (1 − Ē) against the square root of time for samples adsorbing moisture from (a) 0 to 7.5% MC, and (b) 7.5 to 15% MC.

fusion coefficient (Stamm 1964; Choong and Fogg 1968; Avramidis and Siau 1987). This is done by plotting (1 − Ē) against the square root of time, determining the slope of the initial linear portion, squaring it, and then using Eq. (2) to solve for D̄. The average values of the integral diffusion coefficient of bamboo calculated in this manner are summarized in Table 1. The transverse moisture diffusion coefficients for wood of similar density (0.55 g/cc based on oven-dry weight and volume) as the bamboo were calculated using the theoretical model proposed by Siau (1984) and are included in Table 1. It is clear from these values that although the diffusion coefficient of bamboo is about half that of wood, the response of the two materials to temperature and moisture content variations is very similar.

Analysis of variance shows that the main factors (moisture content range and temperature), together with their interaction, are significant at the 1% probability level. The graphs of D̄ versus moisture content range (Fig. 2) and of the logarithm of D̄ versus the reciprocal of temperature (Fig. 3) indicate that the significance of the interaction effect is due to the fanning out of the values of D̄ with increase in moisture content range and temperature. This means that at elevated temperatures, moisture content becomes a less dominant factor on the resistance of bamboo to moisture movement. Similarly, at high moisture levels, temperature has a lesser effect on the internal resistance to moisture flow. The same conclusion for wood was reached by Wengert (1975) upon analysis of Stamm's theoretical diffusion data (Stamm 1946).

It may be observed in Fig. 2 that D̄ is consistently higher in samples subjected to moisture adsorption from 7.5 to 15% MC than from 0 to 7.5% MC. This suggests that the diffusion of water in bamboo is concentration-dependent. Since only two levels of moisture content range were tested, it is not clear whether the relationship between D̄ and moisture content is linear or not. Most studies on wood also demonstrate a strong dependence of the diffusion coefficient on moisture content. Some investigators have reported that moisture diffusion in wood in the radial direction increased linearly with moisture content; others obtained an exponential relationship; while a few observed D̄ to increase with moisture content

TABLE 1. *Integral diffusion coefficients of bamboo at different temperature and moisture content range levels. Also included are the transverse moisture diffusion coefficients for wood of similar density as the bamboo.*

Temperature (C)	Moisture content range (%)	Diffusion coefficient (m^2/sec)	
		Bamboo[a]	Wood[b]
20	0 to 7.5	8.62×10^{-12} (8.85×10^{-13})	2.21×10^{-11}
20	7.5 to 15	2.96×10^{-11} (1.38×10^{-12})	4.83×10^{-11}
30	0 to 7.5	1.52×10^{-11} (1.90×10^{-12})	3.66×10^{-11}
30	7.5 to 15	4.95×10^{-11} (2.49×10^{-12})	7.76×10^{-11}
40	0 to 7.5	2.47×10^{-11} (1.44×10^{-12})	5.85×10^{-11}
40	7.5 to 15	7.53×10^{-11} (2.95×10^{-12})	1.21×10^{-10}
30	15 to 7.5	8.18×10^{-11} (4.17×10^{-12})	—

[a] Arithmetic mean of 4 replicates. Value in parentheses indicates the standard deviation.
[b] Calculated using the theoretical model proposed by Siau (1984).

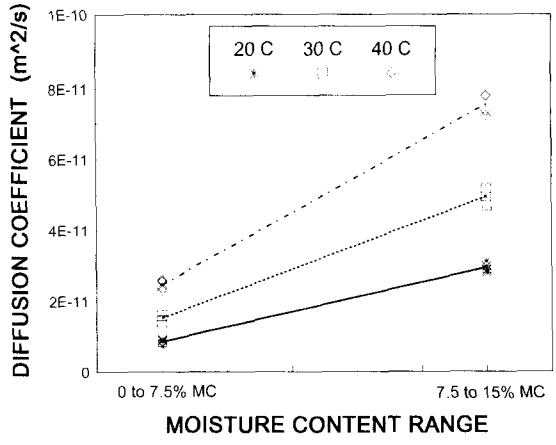

FIG. 2. Graph of the integral diffusion coefficient as a function of moisture content range at three different temperatures (20, 30, and 40 C).

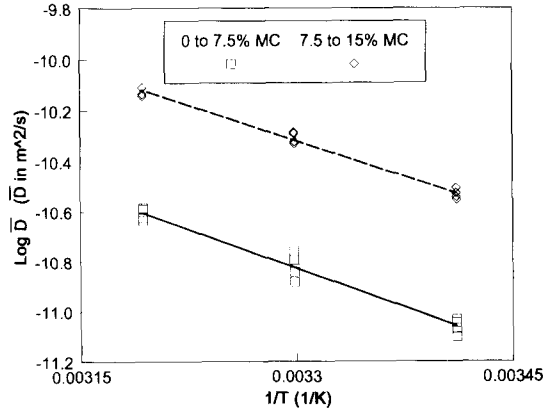

FIG. 3. Relationship between the logarithm of the diffusion coefficient and the reciprocal of the absolute temperature.

up to a certain point beyond which $\bar{D}$ decreases (Choong 1962; Wengert 1975; Simpson and Liu 1991). The increase in the diffusion coefficient with moisture content is often explained in terms of the force of attraction between water and the sorption sites within the material. Bamboo, being a cellulosic material like wood, is expected to hold water by polymolecular adsorption. At low moisture contents, the water molecules are bound directly to the sorption sites. As more moisture is adsorbed, the water molecules are held layers away from the sorption sites and thus are less tightly bound, resulting in enhanced mobility or ease with which water molecules can jump from one site to another in the direction of lower concentration. Furthermore, at high moisture contents, the cell wall is swollen, causing the wall structure to open up, thereby facilitating moisture movement which otherwise would have been restricted since the microfibrils are closer to each other at low MC.

As shown in Fig. 3, the diffusion coefficient also increases with temperature at both moisture content levels. This relationship appears exponential, with the increase in $\bar{D}$ being more rapid when temperature rises from 30 to 40 C than from 20 to 30 C. This temperature-dependence of $\bar{D}$ suggests that the movement of moisture in bamboo is an activated process. From the kinetic theory standpoint, when temperature is raised, a greater fraction of water molecules would gain enough kinetic energy to overcome the potential energy barrier that keeps them bound to particular sites in the material. Since the rate of movement is directly proportional to the number of molecules with energy in excess of the bonding energy, raising the temperature would result in a higher diffusion coefficient. Using the Arrhenius equation, it is possible to calculate the magnitude of the activation energy:

$$A = -2.303R\frac{d(\log \bar{D})}{d\left(\frac{1}{T}\right)} \qquad (3)$$

where A is the activation energy; R, the gas constant; $\bar{D}$, the diffusion coefficient; and T, the absolute temperature. As shown in Fig. 3, the relationship between the logarithm of $\bar{D}$ against the reciprocal of the absolute temperature is linear, with the regression analyses yielding R^2 values of 0.97 and 0.99 for the diffusion experiment over the moisture content range of 0 to 7.5% MC (lower curve) and 7.5 to 15% MC (upper curve), respectively. The slopes of these lines, when plugged into the Arrhenius equation, yield activation energies of 39,875 J/mole for the 0 to 7.5% MC

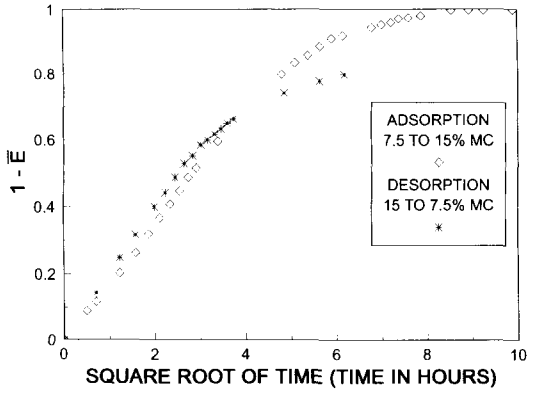

FIG. 4. Scatter plot of $(1 - \bar{E})$ against the square root of time for samples (a) adsorbing moisture from 7.5 to 15% MC, and (b) desorbing moisture from 15 to 7.5% MC.

range and 35,889 J/mole for the 7.5 to 15% MC range. These are comparable to the activation energies for moisture movement in wood which range from 39,775 J/mole at an average moisture content of 2%, to 29,726 J/mole at an average moisture content of 28% (Siau 1984).

Figure 4 and Table 1 show that at 30 C and moisture content range of 7.5 to 15%, the diffusion coefficient was twice as high on desorption as on adsorption. Similar results were obtained by Choong and Fogg (1968) on the diffusion of water in six different wood species. This observed variation of $\bar{D}$ with direction of sorption is clearly a violation of Fickian diffusion, which requires that the coefficient for adsorption be equal to or greater than that for desorption if diffusion is concentration-independent or dependent, respectively. Hence it is apparent that just as in wood, other mechanisms are contributing to the movement of water in bamboo. The higher $\bar{D}$ on desorption is often explained in terms of molecular deformation occurring in the material. For moisture to move from one sorption site to the next, an empty space of sufficient volume must be created to accommodate the water molecule. The formation of this space is a result of the movement of the cell-wall components. During the desorption process, not much energy is needed to create the spaces since the cell wall is in a swollen state. However, after water is removed from the cell wall, the fibrils get closer to each other and their sorption sites (hydroxyl groups) become energetically satisfied by other hydroxyl groups in the wall matrix. Hence during adsorption, more energy is required to open up the wall structure and to break the hydrogen bonding between sorption sites. This results in a slower penetration of water in the material during adsorption compared to that during desorption. The effects of sorption hysteresis, heat of sorption, and driving force variation are also often cited to explain this observed behavior.

SUMMARY AND CONCLUSIONS

The moisture diffusion coefficient in bamboo measured using the unsteady-state approach behaves in a similar manner as that obtained for wood. Diffusion is shown to be moisture content dependent and is observed to be a temperature-activated process. The difference between the adsorption and desorption values indicates that the flow of water in bamboo is non-Fickian, with factors other than diffusion probably contributing to moisture transport.

REFERENCES

ADAMSON, W. C., G. A. WHITE, H. T. DERIGO, AND W. O. HAWLEY. 1978. Bamboo production research at Savannah, Georgia, 1956–77. U.S. Department of Agriculture Agricultural Research Service ARS-S-176, New Orleans, LA.

AVRAMIDIS, S., AND J. F. SIAU. 1987. An investigation of the external and internal resistance to moisture diffusion in wood. Wood Sci. Technol. 21:249–256.

CHEN, M. 1973. Giant timber bamboo in Alabama. J. Forestry 71(12):777.

CHOONG, E. T. 1962. Movement of moisture through softwood in the hygroscopic range. Ph.D. thesis, SUNY College of Environmental Science and Forestry, Syracuse, NY.

———, AND P. J. FOGG. 1968. Moisture movement in six wood species. Forest Prod. J. 18(5):66–70.

FARRELLY, D. 1984. The book of bamboo. Sierra Club Books, San Francisco, CA.

GLENN, H. E. 1950. Bamboo reinforcement in portland cement concrete. Engineering Experiment Station Bulletin No. 4, Clemson University, Clemson, SC.

———. 1956. Seasoning, preservative and water-repellent treatment, and physical property studies of bamboo. Engineering Experiment Station Bulletin No. 8, Clemson University, Clemson, SC.

LEE, A. W. C., X. BAI, AND P. N. PERALTA. 1994. Selected physical and mechanical properties of giant timber bamboo (*Phyllostachys bambusoides*) grown in South Carolina. Forest Prod. J. 44(9):40–46.

LIESE, W. 1987. Research on bamboo. Wood Sci. Technol. 21:189–209.

MCCLURE, F. A. 1957. Bamboos of the genus *Phyllostachys* under cultivation in the United States. Agricultural Handbook 114. U.S. Department of Agriculture, Washington, DC.

MCILHENNY, E. H. 1945. Bamboo, a must for the South. Am. Horticult. Mag. 24:120–125.

NAFFZIGER, T. R., R. S. MATUSZEWSKI, T. F. CLARK, AND I. A. WOLFF. 1960. Dissolving pulps from domestic timber bamboo *Phyllostachys bambusoides*. Tappi 43(6): 591–596.

SIAU, J. F. 1984. Transport processes in wood. Springer-Verlag, Berlin, Germany.

SIMPSON, W. T., AND J. Y. LIU. 1991. Dependence of the water vapor diffusion coefficient of aspen on moisture content. Wood Sci. Technol. 26:9–21.

STAMM, A. J. 1946. Passage of liquids, vapors, and dissolved materials through softwoods. Technical Bulletin No. 929. U.S. Department of Agriculture, Washington, DC.

———. 1959. Bound-water diffusion into wood in the fiber direction. Forest Prod. J. 9(1):27–31.

———. 1964. Wood and cellulose science. Ronald Press, New York, NY.

STURKIE, D. G., V. L. BROWN, AND W. J. WATSON. 1968. Bamboo growing in Alabama. Alabama Agricultural Experiment Station Bulletin 387. Auburn University, Auburn, AL.

VERGNAUD, J. M. 1991. Liquid transport processes in polymeric materials. Prentice-Hall, Princeton, NJ.

WENGERT, E. M. 1975. Prediction of moisture content in wood. Ph.D. thesis, University of Wisconsin, Madison, WI.